Modeling the Antenna Configuration of a Digital Very-High Frequency (VHF) Direction Finding System

by

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Abstract

The U.S. Coast Guard Academy (USCGA) has developed a prototype Digital Very High Frequency super-heterodyne Direction Finding system (DVHF-DF) in support of the U.S. Coast Guard's National Distress Response System Modernization Project (NDRSMP). This receiver, which processes four independent channels of in-phase (I) and quadrature (Q) data, offers significant advantages over more conventional receivers. Specifically, receivers that can archive separate channels of I and Q data can perform post-processed spatial filtering to enhance intelligibility of the demodulated signals, they can perform direction finding independently on two or more signals in the same frequency band originating from different directions, and they can use archived data to perform speaker and platform identification, thereby assisting in hoax determination. The central interest in this paper is a study of the antenna array. Analysis of the array is presented for an array of isotropic radiators, and for a Numerical Electromagnetics Code (NEC) model of the individual elements in the configuration of the actual array. Comparisons of these arrangements are presented.

Introduction

Annually, the Coast Guard (CG) responds to approximately 40,000 calls for assistance. In fiscal year 2001 alone, the Coast Guard saved over 84 percent of all mariners in distress, over 4,100 lives [1]. This legitimate humanitarian work, coupled with the added burden of responding to hoax distress calls, creates a significant workload for U.S. Coast Guard assets. As noted by the National Transportation Safety Board (NTSB) in their 5 October 1999 press release regarding the loss of sailing vessel Morning Dew, the Coast Guard's ability to respond effectively to distress calls, and to identify hoax calls, would be improved by installing Direction Finding (DF) equipment that is capable of providing position fixes on incoming calls, and capable of recording, retrieving, and reviewing DF data [2].

Unfortunately, much of the Coast Guard's current communications equipment is outdated. Thus, the National Distress and Response System Modernization Project (NDRSMP) was initiated to respond to the need for improved communications and sensing capabilities [3]. Acting as technical advisors to assist our colleagues in NDRSMP, the United States Coast Guard Academy (USCGA) has developed a prototype Digital Very High Frequency Direction-Finding system (DVHF-DF) which shows promise as a "proof of concept evaluation platform" as we examine new frontiers in DF technology [4]. More specifically, our system can be used to test proposed DF algorithms, new Digital Down-Converter (DDC) technology ("software radio" concept), phased array antenna configurations, and new platform and speaker identification methods. The system can also be used to evaluate ways of organizing, viewing, and processing contact information.

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The General Approach

The antenna array consists of four elements, corresponding to the four complete RF channels of our system (Figures 1a and 1b). Channel #1 (upper antenna in Figure 1a) is used as a reference antenna. All phase measurements are referred to the Channel #1 antenna. During system development and testing, results were less repeatable than we expected. At some bearings the antenna seemed to give reasonable results, while at other bearings the results were unpredictable. This led to various system validation tests, and bearing resolution tests. Herein we report on the analysis of the antenna array system.

To gain an understanding of the behavior of the antenna array, we undertook a two-pronged investigation. The first part involved an analysis of the individual array elements as isotropic sources. The second part was a study of the array characteristics using an electromagnetic model of the antenna array and the Numerical Electromagnetics Code (NEC). In both cases we illuminated the array with a vertically polarized uniform plane wave emanating around the horizon at three-degree increments. We calculated the magnitude and phase of the received signal at each array element. From these data, we evaluated the performance of the array with and without inter-element coupling. The results of these two approaches were compared.

The isotropic (MATLAB™) model – We assumed for this development that an isotropic receiving element was located at each element point in the array. Using fundamental plane-wave propagation theory we analyzed the anticipated absolute phase of the signal received at each element location as the far-field source was moved around the array. We calculated the expected phase differences between pairs of isotropic elements to determine how the array should work with ideal, non-interacting receiving antenna elements. Next, we modeled a first-order reradiated interaction between element pairs.

The NEC model - For this analysis, we modeled each element of the array as a quarter wave vertical monopole with a radial ground screen made up of thirty-six horizontal wires simulating an aluminum disc. Figure 2 shows a pictorial view of the NEC model of the antenna array. At the feed of the vertical element, we loaded the base segment with a resistive load of fifty ohms. The Numerical Electromagnetics Code (NEC) calculates the magnitude and phase of the current in every segment in the model. By recording the current in the terminating resistor segment, we could compare the magnitude and phase of the electric signal presented to each input channel of the receiver. Our study compared these currents for each antenna element in the array.

The Specific Analyses

The Theoretical Isotropic-Element Array – To study the behavior of the antenna array made up of individual isotropic elements, we computed the "absolute" phase of the signal for each element at its position in the array using Equations 1 through 4. The phase differences were calculated by taking the difference between the "absolute" phases for each pair of elements (1-2, 1-3, and 1-4). These phase differences, based solely on the propagation of a uniform plane wave gave the results for the "ideal" antenna array.

The next step in the analysis was to model the interaction of the elements. To do this, we assumed a first-order reflection of the signal from one of the elements to the other element of the pair. We included only single reflections for each pair of elements. One way to model this reflection is to say that an attenuated version of the signal received by antenna number 1 is reradiated to antenna number 2. Mathematically, the signal at each element can be represented as a linear combination of the direct signal and the reflected signal from the other element of the pair. The reflected signal must include the phase delay associated with the distance from the reradiating element to the receiving element. This result is expressed in Equation 5.

Finally, a phase difference was computed for each pair. Figure 3 shows a plot of phase difference versus bearing for the element 1-2 pair. Both the isotropic phase difference and the first-order reflection phase difference are shown in this plot. Because the two results are nearly identical, we calculated the difference between both phase-difference pairs. The resultant difference of phase differences shows the impact of the interactions between elements of the array. This impact of interaction between the two models is shown in Figure 4.

To model all the elements in the array with only first-order reflections, the total signal for each element is described by equation 6.

As of this writing, we have completed the analysis of weighting functions for only the pair-wise elements, but not for the entire array including all four elements and first-order interactions.

$$s_1(t) = \mathcal{Re}\left\{Ae^{j\omega t}e^{jk0}\right\} \tag{1}$$

$$s_2(t) = \mathcal{Re}\left\{Ae^{j\omega t}e^{jkd_{12}\cos(\phi)}\right\} \tag{2}$$

$$s_3(t) = \mathcal{Re}\left\{Ae^{j\omega t}e^{jkd_{13}\cos\left(\phi+\frac{\pi}{6}\right)}\right\} \tag{3}$$

$$s_4(t) = \mathcal{Re}\left\{Ae^{j\omega t}e^{jkd_{14}\cos\left(\phi-\frac{\pi}{6}\right)}\right\} \tag{4}$$

$$\begin{bmatrix} s_{T1}(t) \\ s_{T2}(t) \end{bmatrix} = \begin{bmatrix} 1 & \kappa_{12} \\ \kappa_{21} & 1 \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} s_{T1}(t) \\ s_{T2}(t) \\ s_{T3}(t) \\ s_{T4}(t) \end{bmatrix} = \begin{bmatrix} 1 & \kappa_{12} & \kappa_{13} & \kappa_{14} \\ \kappa_{21} & 1 & \kappa_{23} & \kappa_{24} \\ \kappa_{31} & \kappa_{32} & 1 & \kappa_{34} \\ \kappa_{41} & \kappa_{42} & \kappa_{43} & 1 \end{bmatrix} \begin{bmatrix} s_1(t) \\ s_2(t) \\ s_3(t) \\ s_4(t) \end{bmatrix}. \tag{6}$$

where:

A = a normalized electric field amplitude $\left(\frac{\text{Volts}}{\text{meter}}\right)$,

$k = \frac{2\pi}{\lambda}$,

$\phi =$ angle from a north-pointing vector to the radiating source in an clockwise direction,

$\kappa_{ij} = \frac{\alpha}{d_{ij}^2} e^{-jkd_{ij}}$,

$\alpha =$ an empirically determined weighting factor

$s_{Tj}(t) =$ total signal at the jth element including a first reflection,

$d_{ij} =$ the length of the position vector from element i to element j.

The NEC model – We used the NEC to analyze the performance of the antenna array with incident plane wave illumination. The procedure we followed was to illuminate individual ground-plane antenna elements as the source was moved around the array in three-degree steps. The magnitude and phase of the current developed in the 50-Ω termination of each element was recorded. With the results of this process, we applied linear superposition to derive the theoretical characteristics of the entire array without element interactions. Next, elements were added to the array as pairs of antennas. Again the magnitude and phase of the induced current was observed. Finally, all four elements were included in the array. This result should mimic the behavior of the complete antenna system operating in free space.

The induced current magnitude and phase records of individual elements were analyzed, calculating non-interacting phase-differences, and interacting phase-differences for each set of pairs. Typical phase difference results are presented graphically in Figure 5 for pair 1-2. Both the non-interacting phase difference and the interacting phase difference are shown. Figure 6 presents the difference between the two curves in Figure 5 to accentuate the deviations between the non-interacting and the interacting data sets. These results were then used to compare with the results from the theoretical development using isotropic elements. Refer to Figure 7 to see the comparison between the isotropic model and the NEC model for both interacting and non-interacting data sets for the 1-2 element pair.

Summary

An analysis of the antenna array for a prototype Digital Very-High Frequency (VHF) Direction Finding system has been presented. The array was modeled as individual isotropic receptors using uniform plane-wave theory with no interaction and with first-order interaction between pairs of elements. Next the array was analyzed using the Numerical Electromagnetics Code (NEC) first as independent receptors and then as pair-wise receptors. Finally, the NEC was used to simulate the entire four-element array. Comparison between the two techniques shows excellent agreement between the theoretical model and the NEC models when the antenna elements are used in pairs. Simulation of the entire array using first order interactions of all four elements is not yet completed.

Based on the comparison of these two approaches, we concluded that the antenna array is functioning as intended. Further investigations of the overall system have led us to believe that multi-path reflections of the VHF signals off objects along the propagation path are adding significant bearing measurement noise to the final direction finding results. Future investigations will focus on dealing with these reflections.

Figure 1a. Direction finding system four-element antenna array. Upper three antennas form an equilateral triangle with a separation of 0.866λ, and the upper-lower antenna separation is 2.5λ.

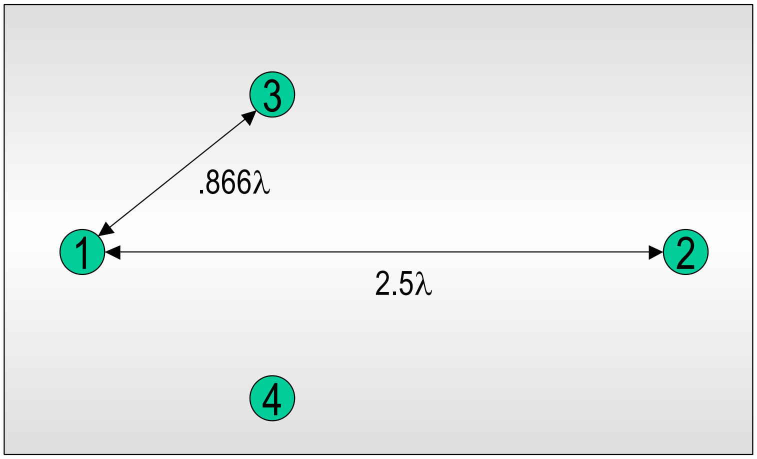
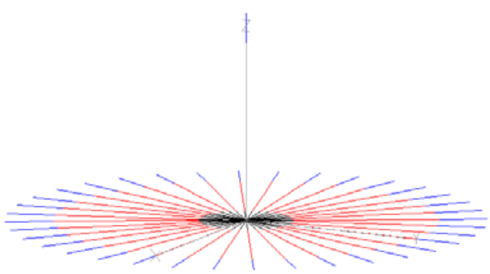


Figure 1b. Direction finding system four element antenna array configuration bird's eye view. Antennas 1-3-4 form an equilateral triangle with sides of length 0.866λ. Our design is based on maximizing the allowable RMS phase measurement error before causing a bearing ambiguity error (50 degrees in this case). The array provides unambiguous bearings in all quadrants, however we achieve a greater degree of accuracy for bearings perpendicular to the long axis.



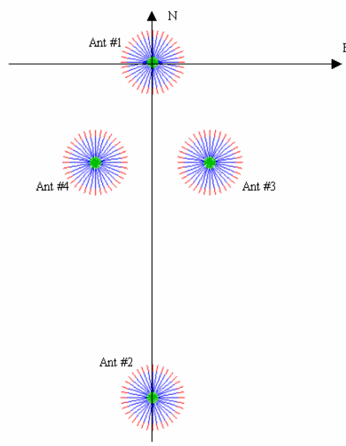


Figure 2. This pictorial illustrates a single ground plane element and a bird's eye view of the entire four-element NEC array model.

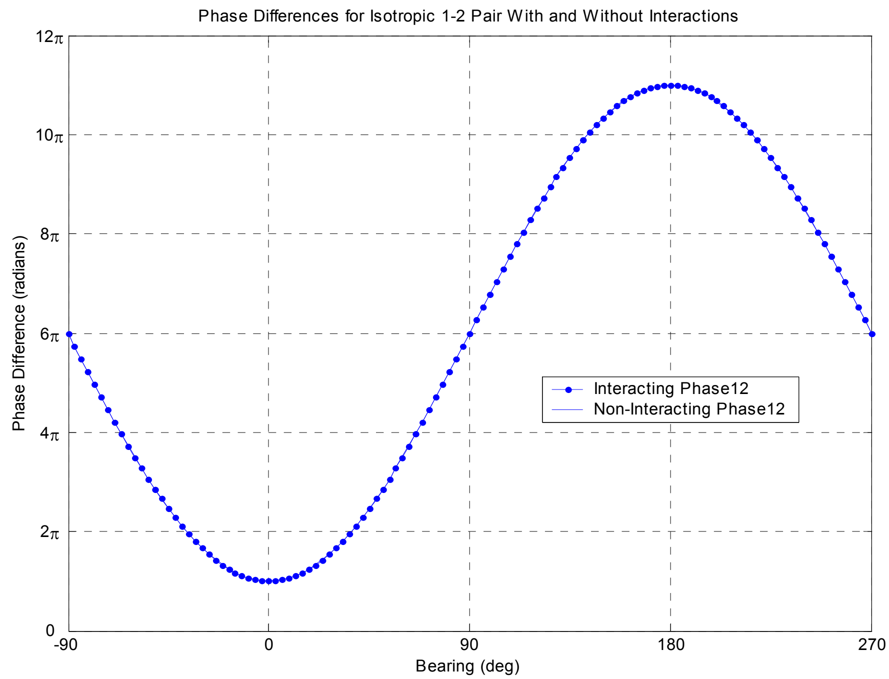


Figure 3. This graph shows the phase difference versus bearing between the isotropic antenna element 1-2 pair assuming no interaction and estimated interaction using a weighting function as described by Equation 5.

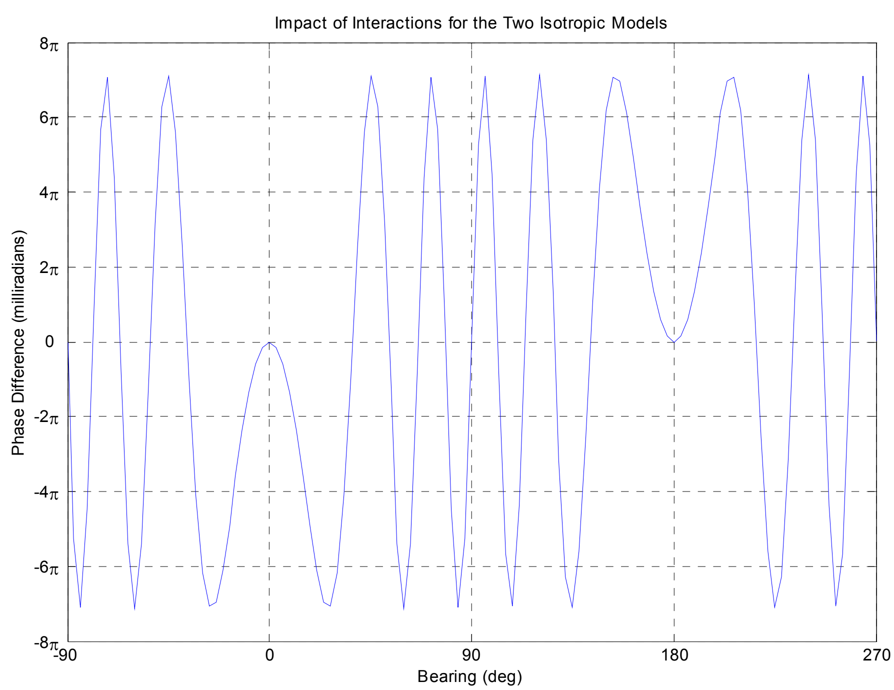


Figure 4. This graph shows the impact of the interactions between the two phase-difference curves shown in Figure 3. To compute this impact, the two curves in Figure 3 were subtracted, and the remainder is shown here.

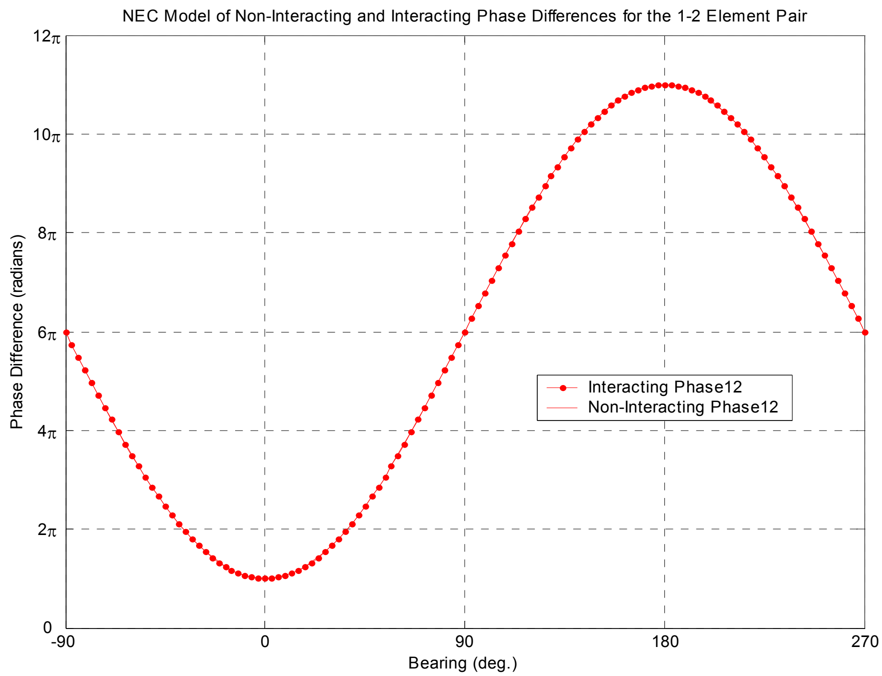


Figure 5. This figure presents the results of the NEC model for the non-interacting 1-2 elements. The non-interacting phase differences are computed by taking the difference between the absolute phase of the signal for each element of the pair modeled with no other elements present. The interacting phase difference is determined by taking the difference between the phases of the signal in each antenna with the other element of the pair in position in the array.

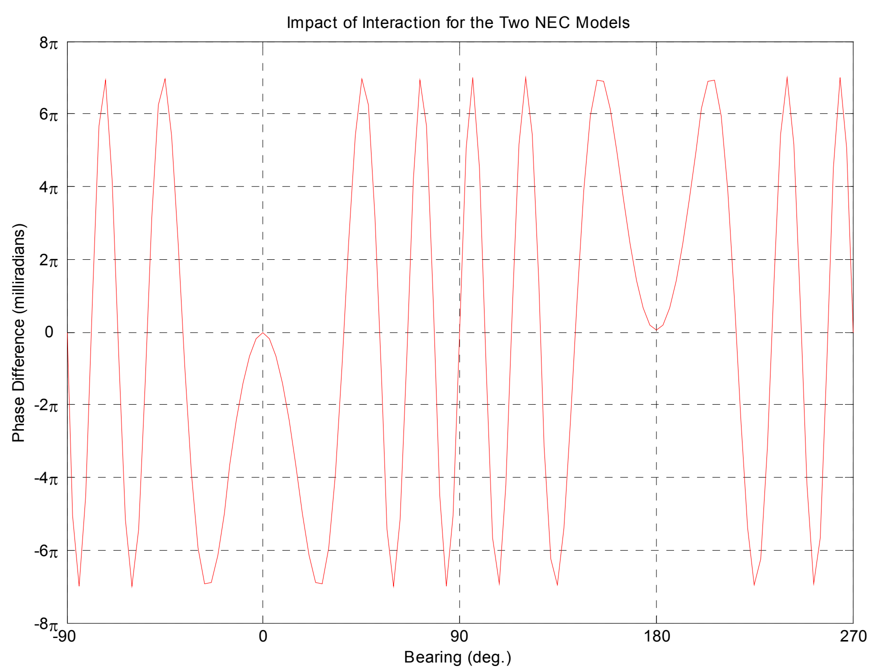


Figure 6. Here the difference between the two data sets in Figure 5 have been subtracted to show the impact of the interactions between the two elements of the 1-2 pair.

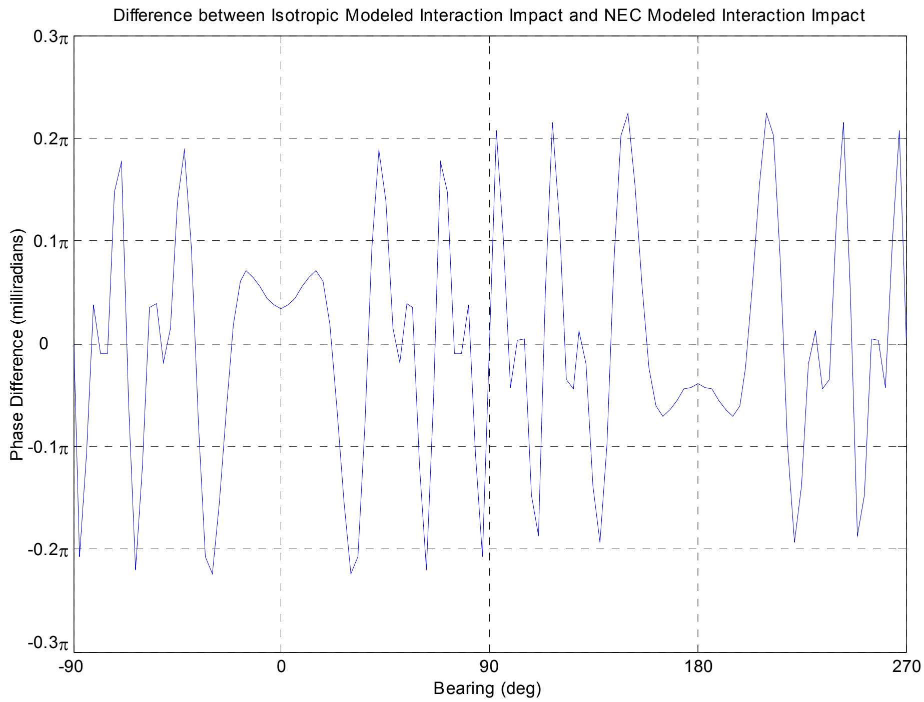


Figure 7. This graph illustrates the difference between the impact of interactions for the isotropic model and the NEC model. Note the vertical scale on this plot is smaller than the scale on any of the preceding graphs, suggesting that the first order re-radiation model explains roughly 96% of the antenna interaction effect on phase differences.

Disclaimer and Note

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard, Department of Transportation, or any agency of the U.S. Government.

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